US Patent Application of

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for

Ultra-Miniature Accelerometers

CROSS REFERENCE TO RELATED APPLICATIONS

This application is related to and claims priority from US provisional application 60/462,510 filed on 4/11/2003, hereby incorporated by reference.

FIELD OF THE INVENTION

This invention relates to miniaturized micromachined accelerometers, especially as applied to biological implants.

BACKGROUND

Several common causes of hearing loss primarily affect the middle ear, but do not significantly affect the inner ear. Such hearing loss is referred to as conductive hearing loss, since transmission of sound to the inner ear is obstructed. Mechanisms for conductive hearing loss include: middle ear infections, excess fluid in the middle ear, eardrum damage due to infection or injury, otosclerosis of the middle ear bones, and rheumatoid arthritis. One approach for treating such conditions is to provide a middle ear implant to restore the functionality of a normal middle ear. In a normal middle ear **160,** as shown on **Fig. 1,** acoustic vibrations set the tympanic

membrane **110** into motion, and this motion is mechanically transmitted in succession through the malleus **120**, incus **130** and stapes **140** before being received by the cochlea **150** of the inner ear. The malleus, incus and stapes are the ossicular bones of the middle ear. The functionality provided by the middle ear is sensing vibration of the tympanic membrane, and providing an acoustic input to the cochlea. A middle ear implant can provide this functionality with a purely mechanical linkage. For example, **Fig. 2** shows an incus replacement **210** connecting malleus **120** to stapes **140**.

Alternatively, as shown in **Fig. 3**, a middle ear implant **380** can sense vibration of the tympanic membrane with a sensor **310** and provide an acoustic input to the cochlea with an actuator **330** driven by a control and power supply circuit **360** responsive to sensor **310**. Circuit **360** is disposed outside the middle ear. In the example of **Fig. 3**, implant **380** includes a sensor package **350** and a separate actuator package **370**. Surface **320** of sensor package **350** is configured to make contact with malleus **120**, and surface **340** of actuator package **370** is configured to make contact with stapes **140**. The approach of **Fig. 3** can provide increased flexibility and/or improved implant performance compared to the approach of **Fig. 2**. Although **Fig. 3** shows a mechanical actuator **330**, an electrical actuator for providing direct electrical stimulation of the inner ear can also be used. Such an electrical actuator can have electrodes in contact with the cochlea and be driven by circuitry **360**. Electrical actuation is the approach taken in several currently available implants. In either case, sensor **310** within sensor package **350** is configured for

implantation into the middle ear. As a result, sensor **310** and sensor package **350** face stringent size requirements, which severely limit the available options for sensor **310**.

For example, a micromachined (MEMS) accelerometer is an attractive choice for sensor **310** in terms of cost and performance, but presently available MEMS accelerometers are too large to be used as sensor **310** in middle ear implant **350** of **Fig. 3**. The smallest present-day MEMS accelerometers typically have length, width and height all larger than 1 mm, which is too large for such middle ear implant applications. A middle ear implant system must have dimensions less than about 1 mm x 1 mm x 4 mm, and within such an implant system, the dimensions taken up by an accelerometer sensor should be about 0.5 mm x 0.5 mm x 1 mm or less. More preferably, such an accelerometer is packaged in a package having a largest linear dimension less than about 0.5 mm. In some cases, it can be desirable to employ multiple accelerometers (e.g., if different accelerometers are tuned for operation in different frequency ranges), and in such cases, the total volume of all accelerometers should also be about 0.5 mm x 0.5 mm x 1 mm or less. Accordingly, it would be an advance in the art to provide a MEMS accelerometer that is small enough for use in a middle ear implant.

SUMMARY

The present invention provides miniaturized micromachined (MEMS) accelerometer-based sensors suitable for use in biological applications, such as a middle ear implant. An encapsulation layer is deposited on top of an accelerometer proof mass and flexure prior to release of

the proof mass and flexure. The encapsulation layer protects the proof mass and flexure from subsequent processing steps, such as dicing and packaging, which enables fabrication of finished devices having reduced size. Preferably, surfaces within the accelerometer are passivated after releasing the proof mass and flexure. Remote piezoresistive sensing is performed in order to provide low noise and reduced sensor head size.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 shows features of a normal middle ear.

Fig. 2 shows an incus replacement in a middle ear.

Fig. 3 shows a middle ear implant having a sensor and an actuator.

Fig. 4 shows a portion of a MEMS sensor according to an embodiment of the invention in a perspective view.

Fig. 5 shows a top view of the sensor of **Fig. 4**.

Fig. 6 shows suitable piezoresistive sensing element locations for a MEMS sensor according to an embodiment of the invention.

Figs. 7a-7i show a preferred processing sequence for fabricating a MEMS sensor according to an embodiment of the invention.

Fig. 8 shows an alternate bond pad configuration for a MEMS sensor according to an embodiment of the invention.

Fig. 9 shows remote piezoresistive sensing according to an embodiment of the invention.

Fig. 10 shows a sensor head package in accordance with an embodiment of the invention.

Fig. 11 shows a sensor head package in accordance with another embodiment of the invention.

Fig. 12 shows a sensor head package in accordance with a further embodiment of the invention.

DETAILED DESCRIPTION

Fig. 4 shows a perspective view of a portion of a MEMS sensor according to the invention. A frame **440** is positioned above a base **410**. A proof mass **420** is disposed within frame **440** and is connected to frame **440** with a flexure **430**. Acceleration imparted to frame **440** causes relative motion between frame **440** and proof mass **420**. Sensing of this relative motion provides sensing of the acceleration imparted to frame **440**. Typically, a sacrificial layer **450** is positioned in between frame **440** and base **410**. During processing, part of sacrificial layer **450** is removed in order to release proof mass **420** and flexure **430** from base **410**, thereby permitting motion of proof mass **420** and flexure **430**.

Fig. 5 shows a top view of the accelerometer of **Fig. 4**. Within line **510**, sacrificial layer **450** (on **Fig. 4**) has been removed. Thus there is a gap between proof mass **420** and base **410** (and between flexure **430** and base **410**) which allows motion of proof mass **420** and flexure **430** responsive to acceleration to be sensed. Sensing such motion of proof mass **420** is preferably performed piezoresistively, as further discussed in connection with **Fig. 9**. For example, as shown on **Fig. 6**, piezoresistive sensing elements **610** can

be positioned on the sides of flexure **430**. As proof mass **420** moves from side to side on **Fig. 6**, flexure **430** bends accordingly, placing piezoresistive sensing elements **610** under tension or compression which changes their resistance.

Figs. 7a-7i show a preferred sequence of processing steps for fabricating a sensor according to an embodiment of the invention. This preferred processing sequence begins with a Silicon-On-Insulator (SOI) wafer having a base **710**, an n-type silicon top layer **711** and an oxide layer **712** separating base layer **710** from top layer **711**, as shown on **Fig. 7a**. Top layer **711** is typically single-crystal silicon, although it can be poly-crystalline silicon for applications which do not require single-crystal silicon. Typical thicknesses for top layer **711** and oxide layer **712** are 20 microns and 2 microns respectively. Top layer **711** is patterned and etched in order to define elements of an accelerometer.

Figs. 7b-7i show regions **714** and **716** corresponding to sections A-A' and B-B' respectively on **Fig. 6**. Thus region **714** on **Fig. 7b** shows a section through a proof mass **720** having holes **718** in it, and region **716** on **Fig. 7b** shows a section through a flexure **722** having p-type piezoresistive elements **724** on its edges. Holes **718** through proof mass **720** facilitate release of proof mass **720** from base **710**, and are preferred but not required. These holes can be as small as about 1 micron in width, since release etching is preferably performed with a gas-phase process, as discussed below.

Piezoresistive elements **724** are preferably fabricated by sidewall ion implantation and annealing. Other methods

can also be used to fabricate piezoresistive elements **724**. For example, piezoresistive elements **724** can be formed by diffusion in a furnace containing boron nitride wafers, where an oxide or nitride mask is used to protect parts of the wafer that will not become piezoresistive elements **724**. It is also possible to fabricate localized deposits of boron-doped glass on the wafer, and then heat the wafer in a furnace to diffuse boron from the glass into the wafer. Sidewall ion implantation is a preferred method because it provides improved uniformity, contacting, and process control compared to alternative approaches. Reference p-type resistive elements **728** on **Fig. 7b** are preferably included in sensors according to the invention, in order to provide a reference resistivity signal from a non-strained portion of the sensor. Such reference resistivity signals can be compared to signals provided by piezoresistive elements **724** in order to improve measurement accuracy. Also shown on **Fig. 7b** is a doped p-plus contact region **726** for making external electrical contact. Since elements **724**, **726**, and **728** are all p-type inclusions in an otherwise n-type layer, elements **724**, **726**, and **728** are electrically isolated from each other. Furthermore, p-type traces, which can be defined by ion implantation, can be used to route signals within the device layer (i.e., layer **711** on **Fig. 7a**).

Fig. 7c shows the result of depositing and patterning an oxide layer **730** on top of the structure of **Fig. 7b**. Oxide layer **730** covers the movable elements of the accelerometer (i.e., proof mass **720** and flexure **722** on **Fig. 7b**). Oxide layer **730** is also patterned to provide isolation for contact region **726**. Oxide layer **730** bridges

the gaps in the structure it is grown on. In order to accomplish this bridging, growth is preferably non-conformal, such that deposition is most rapid on surfaces most exposed to a material source, and is less rapid on less exposed surfaces. Since the top surface (and side walls near the top surface) are relatively exposed surfaces, non-conformal growth is helpful for bridging the gaps. Methods for providing non-conformal oxide deposition are known for various deposition techniques. For example, deposition of a low temperature oxide in a low pressure chemical vapor deposition (CVD) system is typically non-conformal, and non-conformal deposition can also be obtained in evaporation, sputtering, and other CVD processes. Typically, the thickness of oxide layer **730** is comparable to or slightly larger than the gap to be bridged. For example, a 2 micron gap can be bridged by a 3-5 micron thick oxide layer.

Oxide layer **730** bridges holes **718** in proof mass **720**, and also bridges the gap between the frame and the proof mass/flexure assembly. Thus in practice, the gap separating frame from proof mass and flexure is much smaller than shown on **Fig. 4**. We have found a gap of about 2 microns separating proof mass **420** and flexure **430** from frame **440** (all on **Fig. 4**) preferable in practice, since a 2 micron gap can be bridged by oxide **730**, and having a small gap between the frame and the proof mass provides over travel protection by limiting flexure motion to within its elastic range. Furthermore, oxide **730** tends to crack when bridging of significantly larger gaps (i.e., about 5 micron gaps) is attempted. Holes **718** in proof mass **720** can be as

small as about 1 micron in width, as indicated above, and can thus easily be bridged by oxide **730**.

Fig. 7d shows the result of growth of a p-type silicon encapsulation layer **740** over the structure of **Fig. 7c**. The thickness of encapsulation layer **740** is typically from about 10 microns to about 40 microns. The deposition temperature of encapsulation layer **740** is preferably limited to less than about 1000 C in order to avoid diffusion within piezoresistive elements **724**. Single-crystal silicon **742** forms in regions where growth commences on a silicon surface, and polycrystalline silicon **744** forms in regions where growth commences on an oxide surface. After deposition, encapsulation layer **740** can be planarized by chemical mechanical polishing CMP if necessary, to allow subsequent processing steps to begin on a planar surface.

Fig. 7e shows the result of patterning and etching encapsulation layer **740** on **Fig. 7d**. Etch holes **750** and isolation trenches **752** are defined in this processing step. Etch holes **750** allow release etching of the accelerometer elements to be performed, while isolation trenches **752** provide electrical isolation of contact regions such as **754** on **Fig. 7e** from the rest of encapsulation layer **740**. Deep reactive ion etching (DRIE) is a suitable etching technique for this processing step.

Fig. 7f shows the result of a vapor-HF etch applied to the structure of **Fig. 7e**. Patterned oxide layer **730** is removed in this step, as are portions of oxide layer **712** positioned below proof mass **720** and flexure **722**. Thus release of proof mass **720** from base **710** and encapsulation layer **740** is accomplished by forming gaps **760**, and release of flexure **722** from base **710** and encapsulation layer **740** is

accomplished by forming gaps **762**. Gap **764** electrically isolates contact region **754** from other parts of encapsulation layer **740**. The lateral etch rate provided by the vapor-HF etch is about 20 microns/hour. Further information on this vapor-HF process is given in US 5,683,591. Vapor-HF etching is preferred because it does not wet the surfaces of the accelerometer elements, and thereby avoids problems associated with surface tension and stiction that are often encountered when performing release etching with a liquid etchant. Also, a vapor-HF etchant can pass through much smaller holes than a liquid etchant can. Thus etch holes **750** on **Fig. 7e** can be as small as about 1 micron in width, which improves the mechanical strength of encapsulation layer **740**.

Fig. 7g shows the result of thermal oxidation of the structure of **Fig. 7f**. An oxide layer **770** is formed covering all exposed silicon surfaces in the structure of **Fig. 7f**. This can be done by heating the structure of **Fig. 7f** to a temperature of about 950 C in an atmosphere of H_2O and O_2 for about 60 minutes or less. The purpose of oxide layer **770** is to passivate the exposed silicon surfaces on the accelerometer elements. We have found such passivation to be effective for reducing noise in piezoresistive sensing elements. Thus deposition of oxide layer **770** is preferred, but not required, in practicing the invention.

Fig. 7h shows the result of deposition of seal oxide **780** and aluminum bond pad **782** on the structure of **Fig. 7g**. Seal oxide **780** seals off etch holes **750** and isolation trenches **752**, and it is also patterned to define contact points between contact regions **754** and bond pads **782**, as shown. In the structure of **Fig. 7h**, the movable elements

of the accelerometer are completely protected from environmental contamination. Therefore, further processing of the structure of **Fig. 7h** can be performed using conventional methods.

In particular, conventional device dicing and packaging methods can be applied to the structure of **Fig. 7h** to provide the packaged sensor of **Fig. 7i**. On **Fig. 7i**, a package **790**, which can be fabricated with plastic injection chip packaging, surrounds a single accelerometer, and a wire **792** provides an external connection to bond pad **782** and ultimately to doped region **726** (on **Fig. 7b**). For simplicity, only one wire **792** is shown on **Fig. 7i**, although in practice, more than one external contact is typically made. We have found that encapsulation layer **740** can be designed to withstand a pressure of 100 atmospheres, which is an estimated peak pressure encountered during plastic injection chip packaging.

A key point of the processing sequence of **Figs. 7a-7i** is that device encapsulation is almost entirely performed before releasing the flexure and proof mass. This sequence provides improved yield compared to conventional MEMS processing, since released mechanisms are always protected. This sequence also provides reduced device size compared to the conventional alternative of bonding a cap to the base at a late stage of processing. In the present approach, there is no need to allocate device real estate for such cap bonding.

Note that the processing sequence of **Figs. 7a-7h** has defined an electrically isolated vertical contact within encapsulation layer **740** between doped contact region **726** (on **Fig. 7b**) and bond pad **782** of **Fig. 7h**. Thus there is no

need to route signals to the periphery of the device chip, which is also helpful in reducing device size. To further reduce device size, the configuration of **Fig. 8** can be employed, where bond pad **782'** is configured to be substantially laterally aligned with proof mass **720**. By arranging at least one (and preferably all) bond pads in this manner, the device area devoted exclusively to bond pad area is decreased.

In other words, the proof mass area is useful since the mass of the proof mass, which scales with proof mass area, is one of the key parameters determining accelerometer performance. Area devoted exclusively to bond pads is comparatively useless. By positioning bond pads above and laterally aligned to the proof mass, the ratio of useful area to total (i.e., useful + useless) area is increased. Similar reasoning leads to a preference for proof masses having a substantially rectangular shape. Since conventional dicing processes provide rectangular chips, it is easiest to maximize the ratio of proof mass area to device area when the proof mass is also rectangular. It is also preferable to thin base **710** to a thickness of about 200 microns, which reduces device size while still providing sufficient mechanical strength. Preferably, this thinning is performed immediately prior to separation of the wafer into individual devices (e.g., by dicing), to minimize handling of a thinned wafer.

Preferably, piezoresistive sensing is employed in practicing the invention, mainly to provide low-noise remote sensing capability. The resistance of a piezoresistive element can be selected to be anywhere in a range from about 10 Ω to about 10 MΩ or more, by

appropriately selecting doping and geometry of the piezoresistive element. The ability to adjust the resistance value of a piezoresistive element independent from its size is also important. The resistance of the piezoresistive element is determined by the dimensions of its doped region and by the doping density. As the element is miniaturized, the dimensions of the doped region will be reduced, but the resistance value can be maintained.

Specifically, the resistance is proportional to the length/(width*depth) and is inversely proportional to the doping density. If the length/width ratio is maintained, the resistance value can be maintained by keeping the doping density constant and the doping depth constant. If it is necessary to adjust the length/width ratio, the depth and density can be adjusted over a wide range to compensate. By selecting a piezoresistive element having a large resistance, power consumption during operation can be reduced, which is advantageous for applications which require limited power use, such as a sensor operated by a pacemaker.

Alternatively, the use of piezoresistive sensing elements having relatively low resistance (e.g., on the order of 1 kΩ) offers other advantages, especially the ability to perform low-noise remote sensing. This advantage can be appreciated in connection with **Fig. 9**, which shows remote piezoresistive sensing in accordance with an embodiment of the invention.

Fig. 9 shows a sensor head **900** containing a reference resistor **910** and a piezoresistive element **920**. Sensor head **900** is connected to remotely disposed circuitry **970** via wires, or other electrical connections, **940**, **950**, and **960**.

Application of a voltage Vin between wire **940** and wire **960** leads to the generation of a voltage Vout between wire **950** and wire **960**. Variation of the resistance of piezoresistive element **920**, induced by motion of sensor head **900**, causes a variation of Vout for a constant Vin, and this variation of Vout is the desired measurement signal. The configuration of **Fig. 9** is especially appropriate in applications which require small sensor size, since sensor head **900** need not contain circuitry **970** and can therefore be reduced in size compared to a sensor head that includes active circuitry. Preferably, sensor head **900** is embedded within a sensor head package adapted for implantation into a desired location (e.g., middle ear, heart wall, etc.). Preferably such a sensor head package contains only passive electrical components --- i.e., resistors (including piezoresistive elements), capacitors and/or inductors --- and does not contain any active electrical elements (e.g., transistors or integrated circuits containing transistors), to minimize package size. Circuitry **970** typically includes power supply circuitry for providing power to sensor head **900** and sensing/signal conditioning circuitry for receiving signals from sensor head **900**.

However, remote sensing as shown in **Fig. 9** is subject to interference from currents induced on wires **940, 950**, and/or **960** as a result of varying magnetic fields and/or capacitive pickup. These sources of noise are schematically shown as capacitor **930**, and effectively generate a small current I across piezoresistive element **920**. The voltage across piezoresistive element **920** is typically what is measured, as in **Fig. 9**, so the

interference from the noise current I is proportional to the resistance R of piezoresistive element **920**. Thus decreasing R advantageously decreases noise in the remote sensing arrangement of **Fig. 9**.

The ability to reduce noise in a remote sensing arrangement such as shown in **Fig. 9** is an advantage of piezoresistive sensing. Capacitive sensors generally have very large (effective) values of R. For example, a typical capacitive sensor has a capacitance of 1 pF, and at 100 Hz, this effectively gives a resistance of 1 GΩ. Thus such a capacitive sensor is 10^6 times more sensitive to noise current than a piezoresistive sensor having R = 1 kΩ. For this reason, capacitive sensors are usually packaged with integrated active sense circuitry. Such integration of sense circuitry into the sensor head alleviates the above noise issue, but increases the size of the packaged sensor head.

Other sources of noise to consider include temperature noise, Johnson noise and thermomechanical noise. Piezoresistive elements tend to have a strong dependence of resistance on temperature (e.g., a 10 K change in temperature can cause a 20% change in resistance). For the biological applications of greatest interest here, the environment is well temperature-stabilized, and temperature noise is typically not an issue. Johnson noise contributes broadband noise having a power proportional to the resistance of piezoresistive element **920**, and can therefore be decreased by selecting a relatively small resistance (such as on the order of 1 kΩ) for piezoresistive element **920**. For typical devices having sensitivities of 1 mV/g, where g is the acceleration of gravity, the error due to

Johnson noise is on the order of 1 μg, which is well below the environmental background and is thus negligible.

The thermomechanical noise spectral density is given by

$$thermo-mechanical\ noise\ equivalant\ acceleration = \sqrt{\frac{4k_B T\omega_o}{m_p Q}},$$

where k_B is Boltzmann's constant, T is absolute temperature, ω_o is resonant frequency, Q is damping factor and m_p is the mass of the proof mass. A Silicon proof mass having dimensions of 1 mm x 1 mm x 10 μm has $m_p = 10^{-8}$ kg, which gives a thermomechanical noise of 0.1 mg/$\sqrt{Hz}$ assuming Q = 1, T = 300 K and a 1 kHz resonant frequency. Reduction of the proof mass area by a factor of 100 will increase noise by a factor of 10, which may be troublesome for some applications. The damping factor Q can be increased to 100 or more by establishing a partial (or nearly complete) vacuum within the encapsulation, in order to decrease drag on the moving proof mass. Also, the thickness of the proof mass can be increased, to at least 50 microns with the above process, in order to reduce noise by increasing m_p. Other approaches for noise reduction include operation at a lower resonant frequency (i.e., decreasing ω_o) and/or narrowband filtering around the resonant frequency.

A miniature sensor head such as **900** on **Fig. 9** can be embedded in a variety of packages, depending on the intended application. For example, one suitable package is the middle ear implant **350** of **Fig. 3**, and another suitable sensor head packages are shown on **Figs. 10-12**.

Fig. 10 shows a sensor head package **1000** containing a sensor head **1010** remotely connected to active sense

circuitry (not shown) via wire (or wires) **1030**. Sensor head **1010** is preferably a piezoresistive sensor head similar to **900** on **Fig. 9**. Sensor head package **1000** includes barbs **1020** to facilitate implantation into biological tissue. Such a barbed sensor head can be guided to a desired location by a steerable catheter, pressed into contact with the tissue, and then remain lodged in the tissue for long-term continuous or intermittent measurements.

Fig. 11 shows a sensor head package **1100** containing a sensor head **1010** remotely connected to active sense circuitry (not shown) via wire (or wires) **1130**. Sensor head **1010** is preferably a piezoresistive sensor head similar to **900** on **Fig. 9**. Sensor head package **1100** includes barbs **1120** to facilitate implantation into biological tissue. The embodiment of **Fig. 11** differs from that of **Fig. 10** by provision of a sharp tip.

Fig. 12 shows an embodiment of the invention having a sensor head package **1210** disposed at an end of a thin flexible shaft **1220** such that the overall assembly is configured as a needle. Sensor head package **1210** preferably includes a piezoresistive sensor head similar to **900** on **Fig. 9**. Wires **1230** connect sensor head package **1210** to power and signal conditioning electronics (i.e., circuitry **970** on **Fig. 9**). Sensor head package **1210** and/or flexible shaft **1220** can include optional barbs (such as shown on **Figs. 10** and **11**) to facilitate implantation into biological tissues. A miniaturized accelerometer at the tip of a needle has various applications, and can readily be inserted into specific internal biological structures (e.g., bones, tendons, muscles and/or organs) to sense

their movement. In this embodiment, it is important that shaft **1220** be flexible, such that sensor head package **1210** moves with the structure it is implanted into without undue interference from shaft **1220**.

The preceding detailed description of embodiments of the invention is intended to be illustrative rather than restrictive. Thus, the invention can also be practiced by varying many of the above given details. For example, n-type and p-type can be exchanged throughout the discussion in connection with **Figs. 7a-7i**. Also, the preferred processing sequence of **Figs. 7a-7i** provides electrically isolated vertical contacts (e.g., **754** on **Fig. 7e**) through encapsulation layer **740**, which are preferred but not required to practice the invention.

The sensor head package of the present invention can be shaped as a replacement for a biomechanical element, such as an ossicular bone in the middle ear, or as any other mechanical element in any other biomechanical system. The human hearing system is a particular example where placement of an ultra small sensor at various locations provides many benefits. The present invention is also applicable to miniature inertial sensors for hearing, cardiovascular, skeletal, and neuro-muscular studies on small mammals. Such studies in small mammals, such as mice and rats, are important for developing prototype instruments and therapies prior to human trials. For these applications, provision of sensor head packages much smaller than 1 mm is crucial for enabling such studies to be performed.